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New HANE Fireball Physics: Implications for US Infrastructure Vulnerability

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The vulnerability of the US infrastructure to High altitude Nuclear Explosions (HANEs) continues to be the object of studies by a number of blue-ribbon panels and commissions. In particular, studies suggest an alarming sensitivity of our electronic infrastructure to some types of ElectroMagnetic Pulse (EMP) while other types of EMP threaten our power distribution systems. Equally or perhaps more important is the concern that a large percentage of our satellites will experience "upsets" or worse from these same HANE effects. Such studies, however, are all based on the sparse data obtained during the last HANE tests conducted in the early 1960's.

A weakness in our present understanding is that almost all the conclusions about distributed-electric-current-driven EMP, with time scales ½ second or longer, are interpretations of old data guided by the computational MHD/fluid models available at the time. Fluid models make the assumption that the mean-free-path is zero and thus miss important physics regardless of the model used to couple ion motion to the magnetic field. Even when planetary length scales are modeled so that the gyro radius becomes negligible, the early dynamics of the fireball are not properly captured.

The facts are, at relevant altitudes, the explosion expansion is almost unimpeded by the tenuous ionospheric background—particle mean-free-paths are of order 10,000 km. The primary impediment to the debris expansion is the earth's magnetic field bending the energetic ion trajectories emanating from the explosion into circular orbits with typical radii that range from 200 km for heavy ions to 10 km or less for the lighter ions in the debris. These particles thus gyrate many times before they are stopped by a collision with the background atmosphere.

Only models that track ion gyro-motion can recover the myriad possibilities through which the complicated, energetic, "fireball" of debris may evolve. Fireball evolution is important because it determines debris distribution (crucial in satellite vulnerability studies) and generation of low frequency EMP.

With the previous considerations as motivation, we have recently reconsidered the early fireball dynamics to see if more appropriate physics models would reveal new insight into some long-standing problems, such as the apparent need for "jetting" of debris particles to high altitude to explain the observed satellite damage. Additionally, we hoped that the additional physics might reveal new aspects of the early fireball dynamics

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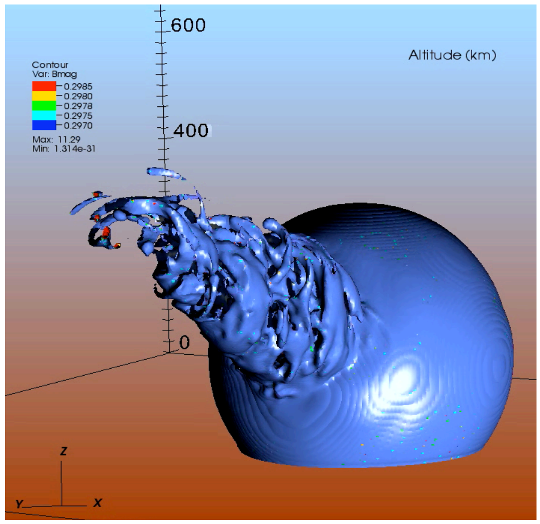
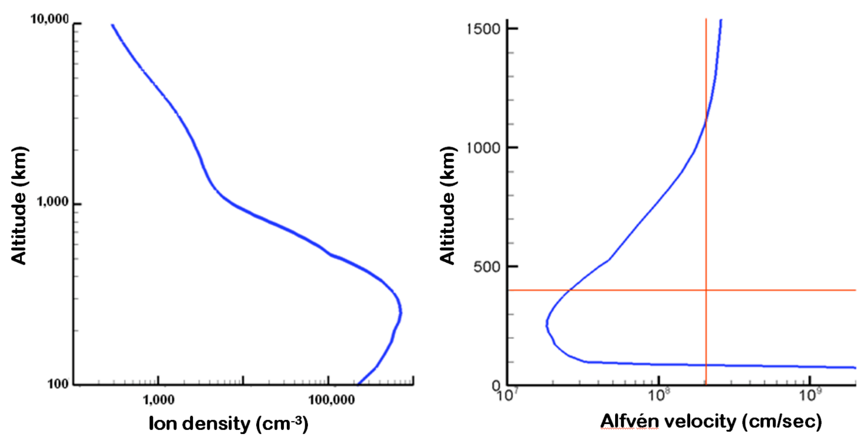
that could augment the rather incomplete understanding we now have of the EMP generated by such tests.

Modern day computers allow us to replace the fluid/MHD ion transport mechanism with a much more capable kinetic algorithm known as Particle-In-Cell (PIC). This replacement opens fireball simulation to the much richer set of plasma modes known to exist in such energetic conditions. We now discuss some of the results of this work

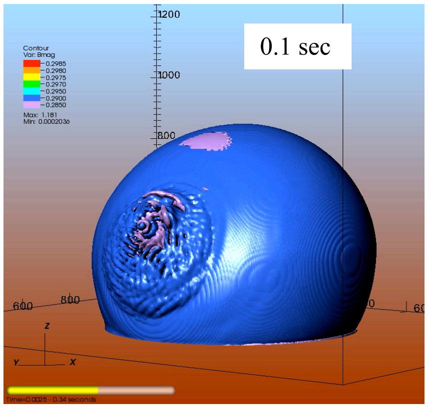
The dynamics of the early fireball do indeed display new and unexpected phenomena. The typical initial conditions for HANE tests are such that the initial debris expansion exceeds the Alfvén velocity. Thus a collisionless magnetic shock forms as the debris expands into the inhomogeneous plasma ionosphere at 400 km altitude. The figure to the right shows both the surface of the shock (blue contour of $\vec{B}$ magnitude) and the induced field created as of some debris jets out along the magnetic field line.

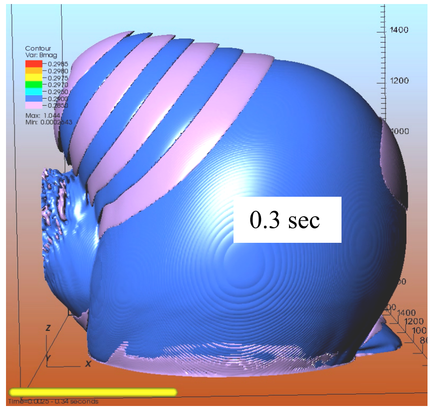


The initially spherical shock distorts as it travels upward due to the ionospheric density gradient and the upper part of the shock wave moves into altitude regions in which the Alfvén velocity $v_{Alf\,ven} = B/\sqrt{4\pi\, n_{ion} m_{ion}}$ in the undisturbed ionosphere exceeds the shock speed.

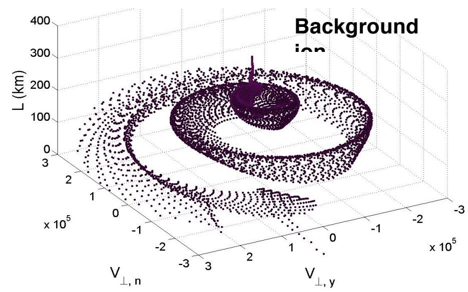


At an altitude of roughly 800 km, the shock can no longer be sustained. Simulation with our kinetic PIC model reveals that the shock disassembles into a variety of waves, one of which is a very coherent circularly polarized plasma wave, strongly resembling a kinetic Alfvén wave.





We suspect that this wave will have implications for both 1) EMP generation and 2) disposition of β-active debris—a crucial factor in satellite vulnerability. Interestingly, the weapon debris is not involved in propagating the coherent wave that emerges from the fireball dynamics. The phase space distribution involves only background ions, but the degree of regularity is remarkable given the chaotic conditions that gave rise to the wave.



We are investigating EMP signals this wave might produce on the ground. Simulations indicate the mode has a wavelength of roughly 60 km and a frequency around 300 Hz. Preliminary estimates indicate that the EMP produced by this mode has an amplitude between the traditional E1 mode, which are very high frequency with amplitude of order kV/m, and the E3 mode that is continental in scale, nearly DC, with amplitude of V/km.

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Perhaps more important than the helical mode is the compressional Alfvén wave generated by the expanding debris. These waves propagate perpendicular to the magnetic field at early times then bend back towards the earth due to the index of refraction arising from the gradient in the background electron density. These waves are roughly 10 times more intense than those in the circularly polarized wave and the refractive effect would bring them down in regions not shielded by the x-ray "patch" immediately below the HANE detonation. These studies have identified two new nonlocal mechanisms that can generate low-frequency EMP.

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